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ART. I.—*The Measurement of Soil Structure.*

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Introduction.

It has long been recognized that soil in its natural state is different from the ground-up material which is analysed in the laboratory for its physical and chemical properties. The particles of sand, silt, clay, and organic matter into which this material may be separated are arranged in nature to form composite units, or aggregates. It is this arrangement which is called the "structure" of the soil. The mechanism by which the aggregates are formed presents a complex fundamental problem on which Russell's work (1934, 1938 i) is outstanding. We are not concerned here with this fundamental problem but rather with its practical outcome and with an attempt to find methods of measuring structure in the laboratory.

A soil of good structure contains a large percentage of aggregates of the order of $\frac{1}{2}$ –1 mm. diameter or a little larger, and these aggregates are stable towards rain. Such a soil allows excess water to drain away rapidly, since the spaces between the aggregates are as large as those between grains of coarse sand. Surface run-off is therefore low, and the risk of erosion is accordingly small. Further, a good structured soil can be easily worked over a wide range of moisture content. A soil of poor structure, on the other hand, contains a big proportion of its fine fractions as individual particles. If there is more than a small amount of dispersed clay present, such soil is sticky when wet, and forms large, hard clods when dry. Such a soil is badly aerated during wet spells, since the spaces between the individual particles are small. It can be worked successfully only between narrow limits of moisture.

Poor-structured soils include not only those which easily become sticky because of their high content of dispersed clay, but also those which are liable to "pack" or set hard after heavy rain. Soils which pack are typically high in silt and fine sand, and low in clay. Their capacity for aggregation is therefore low, especially if organic matter is deficient. They are particularly dense, and since they possess few large pores they may be badly aerated in wet weather in spite of good underdrainage. When cultivated they become powdery, and are liable to erosion by both wind and water. Both roots and shoots may find difficulty in penetrating such hard soils, in contrast to the ease with which plants penetrate through good-structured soil.

It is clear from the foregoing discussion that the structure of soil is of great agricultural importance. There is an urgent need for the development of satisfactory methods of expressing structure in numerical terms, especially if we are to measure and compare the changes that take place under different systems of cultivation or cropping. Since about 1930 the measurement of structure has begun to receive the attention it deserves. Unfortunately a great deal of the most interesting work is available only in Russian; but Hénin (1938) and E. W. Russell (1938 ii) have recently prepared valuable summaries of the experimental methods that have been proposed. The technique of such work must always include some arbitrary rules, and it is to be hoped that workers in different countries will soon reach agreement as to some of these. Meanwhile, we have attempted to arrive at a standard procedure for the study of Australian soils, bearing in mind two important principles: firstly, that the laboratory measurements should give a good correlation with observations in the field; secondly, that the methods should be simple and rapid.

The samples for study were chosen as follows: Firstly, representative soils were taken from well known types with a good or bad agricultural reputation. Secondly, a few types were studied in detail in order to test the effect of differences in management or cropping.

Description of the Soils Studied.

KERIKERI CLAY LOAM.

A highly ferruginous soil from North Auckland, New Zealand. It is derived from basalt, is high in clay, and has an extremely good structure.

PENOLA (S.A.).

A black reclaimed swamp soil, neutral in reaction, high in clay and in organic matter and having a very good structure. Water applied to the surface soaks through with remarkable speed.

BERWICK (25 miles east of Melbourne).

(i) *Black Clay on Oligocene Basalt*.—Of excellent structure, very permeable, rich in organic matter, and non-erosive, although low in exchangeable calcium.

(ii) *Hallam Loam*.—Typical of the podzols found in southern Victoria on the colluvium from hills of Silurian mudstone. Very poor structure, silty, low in humus and colloids and tends to "pack."

TRENTHAM, VICTORIA.

Red loam—rather typical of the soils developed on basalt in the wetter parts of Victoria. A deep friable soil high in clay and having a good structure. This red loam and the black clay from Berwick are probably analogous to the red and black types formed on basalt in Tasmania as described by Stephens (1937).

WERRIBEE (South Central Victoria).

Samples were collected from the State Research Farm, where breeding and manurial experiments on cereals are carried out. The soils are derived from Pleistocene basalt.

(1) The "red" soil, denoted as "Werribee R," is a red-brown clay loam of pH 6, overlying red clay. This surface soil has a poor structure, and is difficult to work. In some winters the water lies on the surface for several days. This soil type is said to have deteriorated in structure since it was first cultivated about 50 years ago. Applications of gypsum at the rate of $1\frac{1}{2}$ to 2 tons per acre cause striking improvements in wet seasons. For example, during the late autumn and winter of 1935 the land remained wet following a total fall of 5 inches of rain in April. Gypsum at the rate of 2 tons per acre applied to experimental oat plots so improved the aeration during the early growth of the plants that the treated plots yielded 51.6 cwt. of hay per acre, as compared to 37.6 cwt. for the untreated. Samples of this red soil were taken both from cultivated paddocks and from land that had been left under native grasses. A rather better type than the prevalent "red" soil was studied in certain green manurial trials which are also discussed later.

(2) The "black" soil, denoted as "Werribee B," occurs in patches up to 20 yards across in paddocks of predominantly red soil. This is a dark grey calcareous clay, of excellent structure. It does not get waterlogged, and is far more fertile than the red type, as may be seen in the spring from the far denser growth of cereals on the black soil.

WIMMERA (Victoria).

The soils are derived from unconsolidated quaternary sediments. Most of the samples were collected near Horsham.

(1) The "red" soil is a red-brown loam overlying red clay, with calcareous clay at a lower level. This type has a rather poor structure, and is inferior generally to the "black" soil, with which it alternates through the district. The sample used in this work, Wimmera R, was collected at Longerenong Agricultural College.

(2) The "black" soil of the Wimmera has become famous for its prolific crops of wheat. This type is a grey calcareous clay. In the natural state it occurs in the formation locally known as "crabholey," in which puffs or hummocks of calcareous self-mulching clay alternate with depressions which are non-calcareous and less clayey. When the land is levelled and cultivated the good structure of the puffs is extended over the whole formation. These soils were studied from three points of view: firstly, the comparison of virgin land with cultivated land; secondly, the comparison of different systems of cultivation of fallows; and thirdly, the association of structure with windblowing. This type is denoted as "Wimmera B," and the puffs and depressions in the crabhole complex as "Wimmera BP" and "Wimmera BD" respectively.

MERRIGUM, GOULBURN VALLEY (Northern Victoria).

This soil is a red-brown loam to sandy loam, neutral in reaction, lying over a clay subsoil, and derived from quaternary sediments. The district includes irrigated orchards and dry land that has formerly been heavily cropped with wheat. It is believed that the structure, which is poor, has deteriorated under cultivation.

RUTHERGLEN (North-eastern Victoria).

The soil of the State Farm at Rutherglen is a greyish-brown non-calcareous sandy loam containing ironstone gravel. The profile is intermediate between the red-brown earths of the Goulburn Valley and the podzolic soils in the wetter country to the south and east. The structure of this soil is very poor. It packs very easily, and its poor aeration during wet spells seriously limits the growth of wheat crops. The soil is particularly variable. The chief interest with this type is the possibility of improvement with vigorous pasture or with green manure.

DOOKIE (Northern Victoria).

A red, good-structured soil derived from metamorphic rocks occurs on a hillside, and a grey calcareous soil similar to the "black" soil of the Wimmera occurs in flat areas which were formerly swampy.

At Werribee, Dookie, and Merrigum, and in the Wimmera, the climate is on the dry side, and when wheat is grown the land is prepared by a year of bare fallow.

Measurement of Structure.

The methods of measuring structure may be classified into two groups, direct and indirect. The direct methods consist simply of separating the soil into fractions of different sizes on a set of sieves. This may be done in air or under water. From these analyses the respective percentages are obtained, either of the actual aggregates or of the water-stable aggregates of various sizes present in the soil at the time of sampling. We shall ignore the former figure, since it represents only a temporary phase of structure which might be completely changed within 24 hours. The indirect methods consist of the measurement of specific physical properties which are thought to be correlated with soil structure. Pore space of the soil *in situ* is probably the most important of these properties.

Measurement of Water-Stable Aggregates.

It must first be decided what is the smallest aggregate that should be included in an analysis. Many Russian writers measure the material of diameter greater than 0.25mm., while others such as Bayer and Rhoades (1932) prefer to include aggregates down to 0.05 mm. or less. These limits correspond roughly to what some workers have described as "macro-structure" and "micro-structure" respectively, and there is as yet no agreement as to their relative importance. Each is dealt with here in turn.

(A) MACRO-STRUCTURE. (Aggregates greater than 0.25 mm.)

The first method for measuring the water-stable aggregates in a soil is associated with Tiulin (1928). It consists simply of washing the soil on a set of sieves by moving them up and down in a bucket of water at a constant rate. Meyer and Rennenkampff's (1936) apparatus consists of a cylinder 40 cm. high in which is placed a set of sieves 9 cm. in diameter and ranging in mesh from 4 mm. to $\frac{1}{4}$ mm. holes. The cylinder is filled with tap-water from below, until the level of the 4 mm. sieve, on which the soil initially rests, is just exceeded. At this point the cylinder is emptied by a siphon, and the filling and emptying continue automatically. In the apparatus as published the sieves are fitted with rubber flanges which touch the walls of the cylinder. These flanges are troublesome to fit and work with and we have not used them in our work.

This apparatus seemed the most promising, and we have accordingly tried to standardize the technique. This has involved certain problems which can be discussed under the following headings:—

- (i) Sampling in the field.
- (ii) Sub-sampling.
- (iii) Pretreatment methods.
- (iv) Time and manner of washing.
- (v) Expression of results.
- (vi) Lower limit of sieves.

(i) *Sampling in the Field.*—This must involve the least possible damage to the natural structure. For this reason we used a sampling tool essentially similar in design to that proposed by Coile (1936). This removes a core 8.5 cm. deep and 442 c.c. in volume, without compaction or other interference, and this sample can also be used to determine the apparent specific gravity and the pore space.

(ii) *Sub-sampling.*—Because of the size of sieves (9 cm. diameter) the maximum sample allowable for any one test is 25 gm. If more is used, there is a risk that the finer aggregates may be retained through the filtering effect of the soil on each sieve. Because of this limitation and the nature of the material collected from the field it is difficult to get a true representative sub-sample. An attempt to improve on the ordinary sub-sampling method was made by using the composite sampling method quoted by Tsyganov (1935). The bulk sample was first separated into four fractions of the following sizes:—greater than 4 mm., 4–1 mm., 1– $\frac{1}{4}$ mm., and less than $\frac{1}{4}$ mm. From these fractions a sub-sample was constructed so that each of them was present in the same proportions as in the bulk sample. It was found on comparison of duplicate results obtained from both sampling methods that there was little difference in variability and we decided that the considerable work involved in the new sampling technique was not warranted. Russell, however (1938 ii) considers that this additional work is worth while.

At this point the problem arises of whether analysis should be done on the field-moist or air-dry material. Since structure is markedly influenced by wetting and drying it is essential to standardize this matter. Selected soils were therefore analysed in the Meyer apparatus before and after drying in the laboratory, and some of the results are given in Table 1. It will be seen that the dried samples have a more stable structure than the fresh soils and also give more erratic results, as is shown by their higher co-efficient of variation. It seems better therefore to analyse the soil in the moist condition, on account of the higher reproducibility as well as the greater approximation to natural conditions.

TABLE I.—COMPARISON OF RESULTS FROM FIELD MOIST AND AIR DRY MATERIAL.
 Figures represent the mean percentages of each fraction. Air dry figures are means of quadruplicates while the Field Moist are means of duplicates.

Soil Type.	Treatment.	Mean Percentages of Fractions.				Standard dev. of material < $\frac{1}{4}$ mm.
		> 4 mm.	4-1 mm.	1- $\frac{1}{4}$ mm.	< $\frac{1}{4}$ mm.	
Werribee R ..	Field moist ..	0.2	6.3	16.8	76.9	4.8
	Air dry ..	12.4	17.7	31.3	38.8	9.1
Wimmera B ..	Field moist ..	0.4	0.7	42.5	56.5	3.4
	Air dry ..	0.6	5.6	52.6	40.7	7.7
Merrigum ..	Field moist ..	0.4	1.8	6.5	90.9	0.1
	Air dry ..	1.3	7.4	26.1	64.1	7.9

(iii) *Pretreatment of Sample.*—The soil may be either placed directly on the sieves or first brought to capillary saturation by moistening from below. Sokolovsky (1933) in a valuable practical review of the whole subject quotes figures to show the stabilizing influence of this capillary moistening. Our own figures confirm his findings (see Table II). We have adopted this method as a routine since it tends to give more nearly equal results for the same soil sampled at different moisture contents.

TABLE II.—COMPARISON OF ANALYSIS ON SOILS WITH AND WITHOUT PREVIOUS CAPILLARY SATURATION.

Soil Type.	Treatment.	Mean Percentages of Fractions.			
		> 4 mm.	4-1 mm.	1- $\frac{1}{4}$ mm.	< $\frac{1}{4}$ mm.
Trentham Red Loam	Capillary soaked ..	12.0	28.0	36.4	25.8
	Flooded ..	10.5	14.9	39.2	35.2
Penola ..	Capillary soaked ..	5.3	53.8	29.0	11.8
	Flooded ..	2.8	43.6	28.4	17.6
Werribee R.2 ..	Capillary soaked ..	0.5	4.2	25.2	72.7
	Flooded ..	0.1	3.1	17.5	79.0
Wimmera B.12 ..	Capillary soaked ..	..	4.1	56.9	38.9
	Flooded ..	..	0.4	26.5	73.1

Another problem concerns the pretreatment of certain soil types such as the Werribee R and Wimmera BD, which become soft and plastic and remain on the 4 mm. sieve although there are obviously no true aggregates of that size in such soils. These soils were shaken with water for various times before being analysed in the Meyer apparatus. When this was done these lumps disintegrated giving a large increase of material less than

$\frac{1}{4}$ mm. diameter. If soils of good structure are subjected to the same treatment there is no appreciable increase of material less than $\frac{1}{4}$ mm. size but only an increase in the intermediate aggregates at the expense of the larger ones (see Table III).

TABLE III.—COMPARISON OF THE EFFECT OF VARIOUS TIMES OF SHAKING DIFFERENT SOIL TYPES.

Soil.	Treatment.	> 4 mm.	4-1 mm.	1- $\frac{1}{4}$ mm.	< $\frac{1}{4}$ mm.	Percentage disaggregation.
Kerikeri (N.Z.) Clay	Not shaken ...	30.8	47.3	13.8	8.0	8.3
	30 minutes shaken	12.6	62.1	17.6	7.9	8.2
Hallam loam ..	Not shaken ...	74.6	10.8	4.9	9.5	10.5
	5 minutes shaken	51.8	15.4	7.2	25.4	28.2
	30 minutes shaken	10.2	15.4	8.2	65.4	73.0
Penola	Not shaken ..	9.0	41.5	26.5	22.4	22.9
	30 minutes shaken	1.0	44.8	27.8	25.2	25.7
Wimmera B (puff) Grassland	Not shaken ...	14.5	37.1	24.2	23.3	25.4
	5 minutes shaken	1.5	31.4	37.2	30.0	32.7
	30 minutes shaken	0.9	31.4	35.2	32.4	35.3
Wimmera B (depression) Grassland	Not shaken ...	27.2	22.6	19.1	31.0	37.3
	5 minutes shaken	6.4	14.3	29.8	49.5	59.5
	30 minutes shaken	0.7	6.6	31.1	61.5	74.0
Merrigum (pasture)	Not shaken ...	57.5	8.8	2.3	31.4	32.0
	5 minutes shaken	16.8	18.6	14.2	50.6	51.4
	30 minutes shaken	8.8	15.8	13.9	61.6	62.5

(iv) *Time and Manner of Washing.*—The soil is washed on the sieves until the outflowing water is completely clear. This usually takes about 20 minutes but may take longer for some soils. Extra washing beyond this stage has no effect on the result. Neither does the long washing appear to disperse the soil more than when done by Tiulin's method. In fact, in spite of the purity of tapwater in Melbourne, those differences that do occur are in the opposite direction to that expected, probably because of the more vigorous swirl of the water in Tiulin's method.

After washing is completed the sieves are separated and dried in an oven at 105°C. and the material from each sieve is weighed after coming to equilibrium with atmospheric humidity. By means of an air-damped rapid balance these weighings can be accomplished in a short time.

After weighing, the material is retained for estimating the amount of coarse sand greater than $\frac{1}{4}$ mm. diameter which must be allowed for in calculating the degree of aggregation of the soil.

(v) *Expression of Results.*—We found that the percentage of “dust”—that is, material less than $\frac{1}{4}$ mm.—was a satisfactory figure by which these results could be expressed. For soils having large amounts of coarse sand the “dust” figures require adjusting as may be shown by the figures in Table IV. From this table it may be seen that the percentage of “dust” calculated in the normal way gives a false impression, making the soil appear better than it is in actual fact. It is preferable to think in terms of the percentage of material less than $\frac{1}{4}$ mm. in the soil which is shown in the Meyer apparatus to be aggregated. The best expression for such a soil is probably the percentage “disaggregation” which is “dust” $\times \frac{100}{100 - \text{coarse sand}}$.

TABLE IV.—TYPICAL FIGURES FOR A RUTHERGLEN SOIL.

Weight of Soil.	Weight of C. Sand.	Weight of material < $\frac{1}{4}$ mm. in Soil.	Total weight of aggregates > $\frac{1}{4}$ mm.	Meyer fraction < $\frac{1}{4}$ mm.	Percentage “dust”.	Percentage disaggregation.
22.24	3.86	18.38	6.18	16.06	72.2	87.4
20.94	4.71	16.23	6.51	14.43	68.9	88.9

(vi) *Lower Limit of Sieves.*—Attempts to include a $\frac{1}{8}$ mm. sieve in the set were unsuccessful owing to the fact that a sieve of that mesh creates considerable resistance to the passage of water which in turn causes serious variability of results.

Summarized Procedure for Meyer Analysis.

(a) Samples are taken from the field by the constant-volume sampler.

(b) After other tests, to be described later, have been made on the sample it can be sub-sampled in the ordinary manner, the sub-samples being of the order of 20–25 gm.

(c) Sub-samples are placed on a filter paper resting in a petri dish of water and allowed to soak in this capillary fashion.

(d) Sub-samples are introduced into the Meyer apparatus and there allowed to wash until the outflowing water is clear.

(e) Sieves are removed, separated and dried in the oven at 105°C.

(f) Material from each sieve is weighed separately after standing in air. This material is retained and dispersed.

(g) All material from sieves is decanted for sand. This sand is passed through sieve of $\frac{1}{4}$ mm. mesh and the coarse sand weighed.

(h) Percentage of “disaggregation” is calculated.

(B) MICRO-STRUCTURE.

Sieves cannot be used for determining aggregates below $\frac{1}{4}$ mm. diameter (see p. 8) and one must therefore rely on Stokes's Law connecting the size of a small particle with its rate of fall through a liquid. Bouyoucos (1935) has used a sensitive hydrometer to give a quick method of measuring the material remaining in suspension after a given time. Cole and Edlefsen (1935) designed a special sedimentation tube in an endeavour to obtain similar results gravimetrically, but we have found that their method is cumbersome and has no advantage over Bouyoucos's method.

Bouyoucos's hydrometer was designed originally for use in mechanical analysis of soil but it has not been widely adopted for this purpose, possibly because his tables for the relation between time of settling, hydrometer reading and particle size do not agree with Stokes' Law. Wintermyer et al. (1931) of the U.S. Bureau of Public Roads, have given this matter some consideration and have made several corrections which can be applied to the hydrometer reading. This has greatly increased the usefulness of the hydrometer.

We have used the hydrometer for measuring the microstructure in nineteen soils. A sample of 50 gm. of each soil was moistened in capillary fashion and placed in a tall cylinder with a litre of water. The soils were first mixed by gently inverting the cylinders six times by hand and the resistance to mechanical disturbance was further tested by taking hydrometer readings after end-over-end mechanical shakings for intervals of 5, 15, 30 and 60 minutes. In every case hydrometer readings were taken after standing for about half a minute and for two minutes.

Sizes corresponding to these approximate intervals are .07 mm. and .035 mm. diameter respectively. Assuming the specific gravity of the aggregates to be 1.93, the exact times of settling required for the measurement of these sizes can be calculated using the Bureau of Public Roads corrections. (The above figure of 1.93 is calculated from the value of 1.50 for the apparent density of an aggregate in air. Naturally it is not a universal figure.)

Analyses of the soils for percentages of sand greater than these two sizes were also made and the percentage disaggregation of the soils calculated for each treatment. From the collection of results in Table V it appears that the best indication of the relative structural merits of the soils is shown by the figure for 0.07 mm. particles after 15 minutes shaking. The size .07 mm. rather than .035 mm. diameter is chosen because it is considered that .035 mm. particles are much too small to be of use in forming a good structure. Fifteen minutes shaking seems to be the optimum amount of treatment necessary to show differences

between good soils such as Wimmera BP1 and bad soils such as Werribce R. Any longer time seems to be equally drastic to all types.

TABLE V.—SHOWING PERCENTAGE DISAGGREGATION OF MATERIAL < 0.07 MM. AND 0.035 MM. DIAMETER RESPECTIVELY AS MEASURED BY THE SOIL HYDROMETER AFTER VARIOUS TIMES OF SHAKING.

Soil.	Percentage disaggregation of material < 0.07 mm. diameter.				Percentage disaggregation of material < 0.035 mm. diameter.			
	No shaking	5 min.	15 min.	30 min.	No shaking.	5 min.	15 min.	30 min.
Wimmera BP1—native grass-land	6	18	27	39	5	14	22	33
Wimmera BD3—native grass-land	21	41	52	68	16	38	47	67
Trentham red loam—under forest	5	14	22	31	3	10	17	25
Penola black clay	2	8	16	22	3	8	13	20
Werribce R1—native grass-land	7	28	43	58	7	28	43	55
Werribce R3—cultivated 30 years	18	45	60	66	16	40	58	63

The procedure for measurement of structure with the hydrometer may be summarized thus:—

- (a) A sub-sample of 50 gm. is moistened in a capillary fashion and placed in a cylinder.
 - (b) The cylinder is then filled up with water to the litre mark.
 - (c) It is shaken end-over-end mechanically for 15 minutes.
 - (d) It is shaken by hand two or three times to mix before putting aside to settle.
 - (e) The hydrometer is read after $\frac{1}{2}$ minute settling, this time being corrected for temperature according to Wintermeyer's tables.
 - (f) The percentage of sand greater than .07 mm. diameter is estimated by settling and decantation.
 - (g) The percentage of disaggregation is calculated.
- The rapidity of this test is a strong point in its favour.

Apparent Specific Gravity and Pore Space as Indications of Structure.

The total pore-space may be divided into two classes, capillary and non-capillary. Capillary pore-space is that within the aggregates themselves and is a measure of the water-holding capacity of the soil. Non-capillary pore-space is that which exists between the aggregates and this indicates the degree of aeration and drainage of the soil. A soil in which both these figures are high combines the drought-resistance of clay with

the good aeration of coarse sand. Non-capillary pore-space is the more important in our investigations; it must necessarily be high in a well-aggregated soil in which the aggregates have the dimensions of coarse sand.

The apparent specific gravity of soil in the field may be used for calculating the total pore-space. Capillary pore-space depends on texture and so remains nearly constant for any one soil type; thus on the one soil, changes of apparent specific gravity represent changes of non-capillary pore space. Naturally one could not expect differences in apparent specific gravity to be correlated with differences between one soil type and another.

We have recorded the apparent specific gravity as simply the weight of the amount of oven-dry soil present in the field sample, divided by its volume (442 c.c.). The total pore-space may be calculated from this if the true specific gravity of the soil material is known. For most soils, it may be estimated approximately assuming a specific gravity of 2.65. The correct measurement of capillary pore-space is particularly difficult, and the problems involved have been fully discussed by Russell (1938 ii).

Apparent specific gravity is a valuable figure, easily and quickly measured, the figures for any one treatment of a particular soil type having a co-efficient of variation of approximately 3-5 per cent.

Crumb Strength as an Indication of Structure.

Several workers have measured crumb strength and have considered it as an indication of the structure of soil. Nikiforoff (1938) suggests that ideal structure combines low cohesion between aggregates with high cohesion within individual aggregates, from which it follows that structure may be estimated from the crushing strength of crumbs. According to Russell's (1934) theory of the nature of crumbs, sandy crumbs should be softer than those consisting almost entirely of clay.

Various pieces of apparatus have been used for measuring this crushing strength. The principle of the apparatus that we have designed is as follows:—A weight which just extends a spring balance to its maximum reading is gradually lowered on to the upper of two long strips of wooden board hinged at one end. The aggregate (2-3 mm. in diameter) is placed between the boards at the end distant from the hinge. On each board is a metal contact, that on the lower one being a flat strip of brass and that on the upper one an adjustable screw. These contacts are situated at the crushing end of the boards quite close to the point where the aggregate is placed.

Since measurements are only to be comparative and not absolute an arbitrary standard of crushing through a distance equal to half the diameter of the aggregate was adopted. The upper contact can be adjusted to suit this condition so that it makes contact when the aggregate has been crushed through

1-1½ mm. The two contacts are connected to an electric circuit in which there is a "buzzer." The force required for such crushing is determined by subtracting the actual reading at the sound of the "buzzer" from the maximum reading on the scale. To facilitate the procedure the scale and weight are lowered by a small windlass.

It was thought that crushing strength would be influenced by the relative humidity with which the soil is in equilibrium but exhaustive tests have shown that there are no significant differences within the range from 35 per cent. to 98 per cent. In some cases slight increases were noticed at 10 per cent. From the series of results given in Table VI it may be seen that there is no correlation between the crushing strength of aggregates and the structure of the soil. It is unreasonable to expect any correlation, since the factors contributing toward crumb strength are so complicated.

TABLE VI.—SHOWING PERCENTAGE DISAGGREGATION OF PARTICLES < 0.25 MM. DIAMETER AND CRUSHING STRENGTH OF UNWASHED AGGREGATES (2-3 MM. DIAMETER) OF 4 SOILS.

	Percentage disaggregation.	Crushing Strength.		
		Mean of 4 samples.	Mean of 20 samples.	Coefficient of variation.
			gms.	
Werribee R1—native grassland	26		360	70
Werribee R2—cultivated	91		1,250	60
Merrigum 1—permanent pasture	32		330	61
Wimmera BP4—native grassland	25		1,210	50

General Discussion.

The first purpose of this investigation is to obtain some numerical expression which indicates the desirability of the structure of the soil under test. In order to show the extent to which this has been achieved Table VII has been compiled showing the values obtained for several soils by three of the tests described in the preceding section, together with the percentage of organic carbon (representing about 58 per cent. of the total organic matter) as found by the rapid approximate method of Tiurin (1931). The several samples have been classified into four groups in order of merit. The basis for this division (which at best must naturally be somewhat arbitrary) is the local reputation or the farmer's opinion or description of the behaviour of the particular soils.

The percentage disaggregation as determined both for material less than 0.25 mm. and 0.07 mm. diameter, gives a good correlation with field behaviour, as shown in figs. 1 and 2. It appears that these two proposed methods will be distinctly useful in further work on soil structure.

There are a few cases in which the field rating disagrees with laboratory analysis. Two grassland soils from Werribee, which

TABLE VII.—SHOWING PERCENTAGE DISSAGGREGATION AS DETERMINED BOTH BY THE MEYER APPARATUS AND ALSO HYDROMETER METHOD ALONG WITH PERCENTAGE ORGANIC CARBON, APPARENT SPECIFIC GRAVITY.

Soil and Treatment.	Percentage disaggregation.		Apparent Specific Gravity.	Organic Carbon.
	< .25 mm.	< .07 mm.		
Group I.—First Class Structure.				
Kerikeri clay	8	..	..	4.23
Penola black clay	23	16	..	5.35
Berwick black clay—under permanent pasture	5	18	0.80	4.10
Dookie red loam—under cultivation ..	33	51	..	1.71
Trentham red loam—virgin forest soil ..	31	22	..	1.16
Wimmera BP4—native grassland	25	24	1.13	1.50
Merrigum 2—lucerne for many years, then 4 years sown pasture	32	..	1.24	1.94
Merrigum 1—natural pasture—greatly im- proved—much subterranean clover ..	32	67	1.24	2.14
Group II.—Good Structure.				
Merrigum 7—untouched native grassland ..	46	..	1.34	2.18
Werribee R4—native grassland	27	..	1.26	1.63
Werribee R1—native grassland	26	43	1.18	2.09
Rutherglen 3—under subterranean clover for 8 years, then cropped year before sampling ..	47	..	..	1.75
Werribee B—long cultivated soil, bare fallow	53	..	0.95	2.22
Wimmera BP1—native grassland	41	27	1.18	0.49
Wimmera BD3—native grassland	54	52	1.48	0.73
Wimmera BD6—native grassland	37	52	1.55	1.49
Wimmera B15—cultivated rough fallow ..	68	..	1.03	0.90
Wimmera BD16—native grassland	25	..	1.20	2.12
Wimmera B18—paddock which had just been cultivated for first time	45	..	..	1.12
Dookie black clay—long cultivated bare fallow	60	62	..	..
Group III.—Rather Poor Structure.				
Wimmera R8—native grassland	61	63	1.65	1.43
Wimmera R19—red patch occurring among black—native grassland	72	..	1.59	1.45
Wycheproof—from "red plains" country in Southern Mallee—native grassland ..	67	..	1.50	1.13
Wycheproof—from "buloke" country in Southern Mallee—native grassland ..	60	..	1.57	..
Group IV.—Bad Structure.				
Merrigum 4—orchard soil—much cultivated ..	96	..	1.34	1.26
Merrigum 5—orchard soil—much cultivated ..	96	71	1.46	1.41
Merrigum 6—wheat—fallow rotation for many years	91	64	..	1.21
Merrigum 8—cultivated for many years—re- verted to native pasture in the last 2 years	82	..	1.67	1.30
Merrigum 9—cultivated for many years—re- verted to native pasture in the last 2 years	88	66	1.66	1.46
Werribee R2—cultivated for many years ..	91	60	1.34	1.34
Werribee R3—long cultivated—treated with gypsum, three years previously	87	57	..	1.39
Rutherglen III. } cultivated for many years	88	..	1.35	0.70
Rutherglen V. } —various green manurial	87	..	1.33	0.96
Rutherglen VII. } treatments	87	..	1.33	0.97
Rutherglen X. }	90	..	1.35	0.63
Rutherglen 4—much cultivated paddock ..	69	..	1.35	1.04
Rutherglen 6—much cultivated paddock—said to be "worn out"	73	..	1.42	0.70

are placed in group II, appear by Meyer's method (fig. 1) to be better than they are. This effect is due to the way in which roots hold the particles together; when these soils are shaken with water as in the hydrometer method the discrepancy disappears (fig. 2). Again, Merrigum 1, a soil which has never been ploughed, seems very good in the field but gives a poor figure after shaking (fig. 2). This may be due to the softness of the crumbs, and suggests that the soil deteriorates quickly under cultivation.

CORRELATION BETWEEN AGRICULTURAL REPUTATION
AND PERCENTAGE DISAGGREGATION (MEYER APPARATUS)

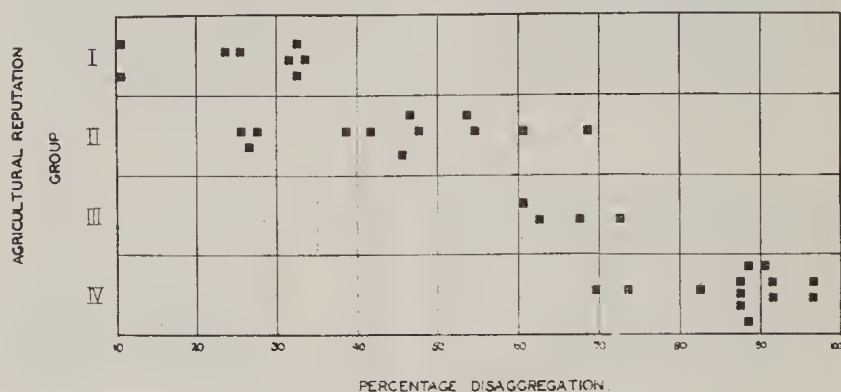


FIG. 1.

CORRELATION BETWEEN AGRICULTURAL REPUTATION
AND PERCENTAGE DISAGGREGATION (HYDROMETER METHOD)

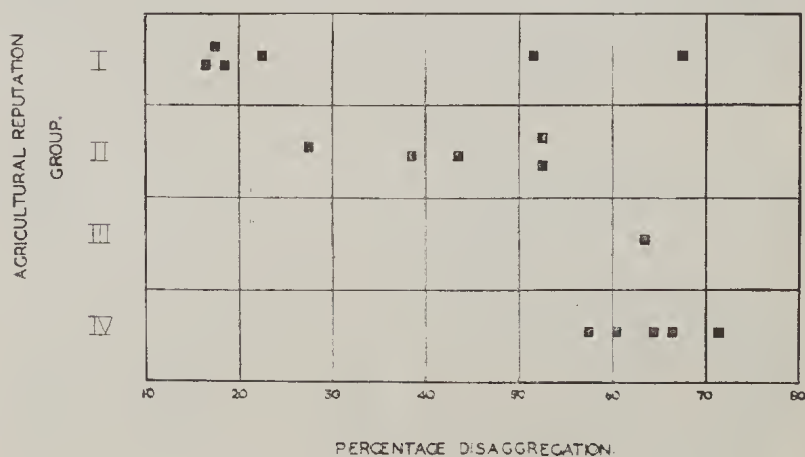


FIG. 2.

From the above discussion it seems to follow that for proper comparison of grassland soils with one another it is desirable to include a shaking treatment in order to form a judgment on the relative merits of such soils after a few years of cultivation.

The results obtained from the Meyer apparatus after various times of shaking and those obtained from the hydrometer method which involves shaking treatment, given in Tables III and VII respectively, form a reasonably sound basis by which the soil types may be classified. A soil having a low percentage disaggregation which alters very little after shaking has a very good structure. The amount of alteration on shaking is probably more important from the practical point of view than the initial percentage disaggregation for it represents what structure that soil may develop when subjected to agricultural practices. On this basis the soil types studied may be placed in order of merit as follows:—

- Kerikeri clay loam
- Penola black clay
- Berwick black basaltic loam
- Wimmera B "puff"
- Trentham and Dookie red loams
- Werribee R
- Wimmera B "depression"
- Merrigum.

COMPARISON OF STRUCTURE WITHIN TYPES.

Probably the most useful application of the measurement of structure is to show up the effects of various treatments on one soil type. Many workers both in Russia and America emphasize the damage to structure caused by cultivation. Bradfield (1937) likened cultivation to a surgical operation, meaning that it should be done only if absolutely necessary—it may do immediate good but in itself is bad. Cultivation is essential for the growing of crops, but a long succession of crop and fallow, without a period under pasture, is undesirable. The red soil at Werribee and certain types in the Goulburn Valley have deteriorated physically under cultivation. In the case of the Werribee soils it is said by some old residents that the deterioration is not only in physical condition but also in crop yields. The "black" soils of the Wimmera with a better natural structure than the two types already mentioned do not seem to have suffered at all.

From Table VIII it may be seen that each cultivated soil shows a greater percentage disaggregation than the respective uncultivated soil. Most of the cultivated soils studied have been farmed on a crop-fallow rotation and it can be seen from the table that they contain less organic matter than the uncultivated soils and in general have a higher specific gravity, except immediately after cultivation.

It is interesting to see how the application of gypsum to the cultivated Werribee soil only brings the density of the soil down to that of native grassland and has apparently little effect on the percentage disaggregation. The differences however were probably more marked two years earlier. Meyer's method is, of course, not suitable for soils which owe their virtue to flocculation by soluble salts.

TABLE VIII.—SHOWING THE DIFFERENCE IN STRUCTURE OF CULTIVATED AND UNCULTIVATED LAND.

Soil.	Treatment.	Percentage disaggregation. Meyer.	Percentage Organic Carbon.	Apparent Specific Gravity.
Merrigum 1 and 2	Improved pasture ..	32	2.04	1.24
" 7 ..	Virgin pasture ..	46	2.18	1.34
" 4 and 5	Orchard—much cultivated	96	1.33	1.40
Werribee R 1 and 4	Native grassland ..	26	2.09	1.18
" R 2 ..	30 years cultivated ..	91	1.34	1.34
" R 3 ..	30 years cultivated, treated with gypsum 2 years previously	87	1.15	1.15
Wimmera B ..	Native grassland ..	25	1.50	1.13
" B ..	Wheat stubble, August, 1938	44	..	1.07
" B ..	Under wheat crop, August, 1938	58	..	0.99

The high specific gravity of some cultivated soils is due to the reduction of aggregates to finer particles which block up the non-capillary pore spaces. This effect of cultivation is not shown on Wimmera soils for it seems that such fine particles have the capacity to regenerate into aggregates of reasonable size within a short space of time. Investigations on plots at Longerenong under crop and fallow have shown that while under crop and not being cultivated the soil tends to regenerate its structure as shown by the results in Table IX. This is not the case with other soils such as Werribee and Merrigum types for on these soils the effect of cultivation is cumulative and the structure gets worse from year to year unless the land is allowed to revert to pasture for a few years.

The effect of pasture on the regeneration of structure has been described by various Russian workers. The beneficial effect of pasture on structure is due to two factors. Firstly, the chemically stabilizing effect of the rapidly decomposing organic matter according to Geltzer (1934). Secondly, besides any such chemical effect there is the mechanical effect of roots holding particles together which would otherwise have passed through a sieve. The relative importance of these two factors is as yet undetermined. Some of our figures also show the good effect of pasture. The Merrigum soil under pasture, a prominent component of

which is subterranean clover, can be compared with an orchard soil which has been constantly cultivated for many years. During the last few years weeds in the orchard have been encouraged in the winter and ploughed under during the spring in order that the increased organic matter might improve the soil both from the point of view of working and irrigating. The orchard soils seen just after a good cultivation gave a good impression and the subsequent poor results given by a Meyer analysis were rather surprising. The results were justified, however, for inspection of the orchard later in the year showed it to be badly

TABLE IX.—SHOWING REGENERATION OF STRUCTURE OF WIMMERA BLACK SOILS DURING A PERIOD OF 12 MONTHS AND ALSO THE DIFFERENCES IN STRUCTURE OF NON-FALLOW COMPARED WITH VARIOUS FALLOW PRACTICES.

		Percentage Disaggregation (Meyer Apparatus).			
		Last cultivated June, 1938— prior to sowing.		Last cultivated June, 1937— prior to sowing.	
		Standard Error.		Standard Error.	
Summer fallow	..	52.2	2.1	39.9	1.7
Winter fallow	..	50.3	2.1	43.4	1.9
Late fallow	..	49.2	2.1	..	..
Non-fallow	..	39.9	1.4	..	..

packed in spite of the green manurial crop which is ploughed in every year. The reason for green manuring orchard soils at Merrigum was to overcome the effects of bad structure. It is quite likely that green manuring although it cannot regenerate the structure of a soil having so much cultivation, does prevent any further deterioration. Our methods are not refined enough to measure such differences as green manuring may bring about on these soils.

GREEN MANURIAL TRIALS.

Structure analyses were done in conjunction with dynamometer trials on green manurial fields at Werribee in 1937 and 1938 and at Rutherglen in 1938. The plots were first laid down in order to compare the relative merits of the rotations: (a) wheat or oats alternating with a year of bare fallow; (b) wheat or oats alternating with a green crop sown in autumn and fed off in late spring; (c) the same as (b) with the green crop ploughed in during late spring. The results with Meyer's method on Werribee samples in 1937 showed that the "fed off" plots were slightly better than the "ploughed in" which in turn were better than those with the crop-fallow rotation. The records of the dynamometer also showed that the fallowed plots were the most refractory. In 1938 however the results were completely at random probably because the plots were very uneven both from the point of view of soil type and topography. At Rutherglen

in 1938 samples taken from the green manurial field showed no differences among treatments. The soil in this field is too variable for such a test to succeed.

WINDBLOWING OF SOIL.

The possibility that the "black" land of the Wimmera might be liable to blowing is suggested by its resemblance to certain areas in the North-American wheat belt which have suffered severely in recent years. Hopkins (1935) has pointed out that soils high in organic matter and lime have blown in past years in America. The Wimmera "Black" soil which is considered to be the best of the Victorian wheat belt has blown in previous years. It seems, however, that a certain set of conditions are required before anything of a serious nature occurs. It is only after a heavy fall of rain in the summer time followed by strong winds that the blowing occurs for then the top layer is disintegrated into small particles which dry quickly, before any regeneration can take place, into a light powdery layer. The blow can be prevented by working this thin layer into the soil as soon as possible after the rain; it is then able to regenerate its structure. We have examined drifts of blown soil and paddocks that have been blown and have found that as regards soil structure one paddock is no more likely to blow than any other. It is obvious that the fineness of the natural structure is connected with the problem, for the crumbs of the Wimmera soils are very small. According to Ilénin (1936) this property is to be expected of calcareous soils.

Deterioration and Regeneration.

It is obvious from the above discussion that structure is by no means a permanent property of the soil, but changes take place in some soils in the course of a few days and in others over a period of years.

By deterioration of structure we mean that the aggregates are breaking down into smaller particles thus blocking the pore spaces, or else the aggregates are losing their capacity to remain as separate individuals and are gradually merging into one another to form a compact mass, thus giving the same effect.

POT TESTS ON WERRIBEE SOILS.

This experiment was designed in the first place in order to check some surprising Russian work by Chizhevsky and Kolobova (1935), comparing the growth of a crop on soils composed of aggregates of various sizes. These were obtained from the red and black soils from Werribee already described (p.). The experiment was inconclusive as regards the relative growth of plants, but as a study of the effect of weathering on aggregates from good and bad soil types it is of interest. The soils were collected from the mulch of a fallowed field and air-dried, after

which each type was sieved into fractions of the following sizes, greater than 12 mm., 12-5 mm., 5-2 mm., 2- $\frac{1}{2}$ mm., and less than $\frac{1}{2}$ mm. diameter. The four smallest fractions were placed in pots, 9 inches in diameter and 30 inches deep, which had been sunk into the ground. Duplicate pots of each fraction (making the total number sixteen) were arranged in the formation of a randomized square. Oats were sown and harvested and with the exception of a general superiority of the yields of the black over the red no conclusive results were obtained. It was decided to leave the pots to stand for twelve months exposed to the weather and then determine the condition of the structure in the top 4 inches and compare this with the analyses done on the original materials. The results in Table X show that all fractions of the black soil have regenerated their structure to a certain extent while the red fractions have not changed significantly. The reason for the slight increase of the material greater than 4 mm. is due to the refractory nature of the clods caused by "packing." This material cannot be called genuine aggregates as in the case of Kerikeri and some other soils, for it becomes paste-like on the sieves and requires slight mechanical action to remove it. On breaking down it passes entirely through the sieves and merely increases the percentage of material less than $\frac{1}{4}$ mm.

TABLE X.—SHOWING STRUCTURE ANALYSES OF VARIOUS FRACTIONS OF WERRIBEE RED AND BLACK SOILS BEFORE AND AFTER 14 MONTHS WEATHERING.

—	Fraction.	Year.	> 4 mm.	4-1 mm.	1- $\frac{1}{4}$ mm.	< $\frac{1}{4}$ mm.
Werribee Red ..	12-5 mm. ..	1937	1.9	3.8	12.5	80.8
		1938	7.3	4.0	13.0	75.7
	5-2 mm. ..	1937	2.0	9.4	11.9	76.7
		1938	8.1	4.3	8.4	79.2
	2- $\frac{1}{2}$ mm. ..	1937	..	5.3	21.5	73.2
		1938	3.5	2.1	12.4	82.0
	< $\frac{1}{2}$ mm. ..	1937	..	..	8.1	91.9
		1938	1.8	..	6.2	92.0
Werribee Black ..	12-5 mm. ..	1937	10.1	11.3	27.7	50.9
		1938	6.7	19.6	35.9	37.7
	5-2 mm. ..	1937	8.2	33.7	25.4	32.6
		1938	19.9	24.8	13.6	31.8
	2- $\frac{1}{2}$ mm. ..	1937	..	7.1	43.8	49.1
		1938	4.5	13.2	46.7	35.7
	< $\frac{1}{2}$ mm. ..	1937	..	..	30.6	69.4
		1938	33.2	2.3	22.9	42.6

LONGERENONG PLOTS.

The regeneration of structure has already been referred to in reference to the results from Longerengong as given in Table IX. The results show that there are no differences in structure caused

by different fallowing systems commonly used in the Wimmera. They do, however, show that after cultivation the percentage disaggregation is higher than at the end of the period during which the soil is under crop and stubble, thus showing that regeneration has taken place. It is only on such soils as these and the Werribee black type that constant cultivation can be carried on without after a few years encountering the difficulties attributable to bad structure. On other soils which do not show this regeneration such as Werribee red, Merrigum and Rutherglen, cultivation for a few years should be rotated with pasture for another period of years the length of which is as yet undetermined.

Summary.

Two methods of measuring the water-stable aggregates of soils are studied in detail and the correlation of these methods with field behaviour is discussed.

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